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DYNAMIC CHARACTERISTICS AND DYNAMIC RESPONSE OF TIMBER FOOTBRIDGES TO DYNAMIC HUMAN ACTIVITIES

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ABSTRACT: The dynamic action of footbridge users in different forms of activity (especially during walking and running) may cause an excessive vibration of the footbridge deck and may disturb the comfort of use of the structure. The dynamic susceptibility of the footbridges varies depending on the construction material used to build the footbridge and the typical construction solutions (construction details) resulting from the construction material used. The paper presents the basic dynamic characteristics of timber footbridges of various structural solutions, collected during dynamic field tests of these structures. The obtained results indicate relatively high dynamic resistance of timber footbridges to the dynamic loads generated by users under normal conditions of use. In addition, the results show that in the case of timber footbridges, it is possible to consider changing the requirements of international standards defining the range of natural frequencies sensitive to the dynamic impact of users. In the case of timber footbridges, characterized by a relatively high self-weight (compared to steel footbridges), high stiffness and high damping, it is possible to consider changing the requirements for performing forced vibration analyses only for structures with fundamental vertical vibration frequency $f_v \leq 3.0$ Hz instead of the currently defined $f_v \leq 5.0$ Hz.

KEYWORDS: Timber Footbridges, Vibration, Dynamics, Damping, Walking, Running, Comfort of Use.

1 INTRODUCTION

Footbridges are perceived as lightweight structures. The main features observed in the design of footbridges, i.e., the scale of the structure adapted to the human scale, a relatively small deck width, often a high slenderness of the structure, and the application of new (lightweight and/or high-strength) materials, can lead to a reduction in the stiffness of the structures and an increase in their dynamic susceptibility.

In a situation of dynamic impact of pedestrians on footbridges, in a large number of cases, steel and composite steel and concrete footbridges with a span length $L \geq 25.0$ m exhibit high dynamic susceptibility. For lengths $L \approx 25.0 \div 45.0$ m, the fundamental natural vibration frequency of steel footbridges is often in the range of the steep frequency f_s of a running person $f_s \geq 2.40$ Hz (Figure 1). The vibration acceleration caused by a single running person can significantly exceed the allowable vibration acceleration value for vertical vibrations $a_{max} \approx 0.50 \div 1.0$ m/s^2 (respectively: maximum and minimum comfort level; 1.0 m/s^2 permitted for rarely occurring vibration) [1-4]. For span lengths $L \geq 35.0$ m, these footbridges also become susceptible to dynamic action of walking users.

The high dynamic susceptibility of the footbridge under the influence of people walking or running may contribute to excitation of its vibrations by vandals jumping or doing squats with a frequency equal to the natural vibration frequency of the structure.

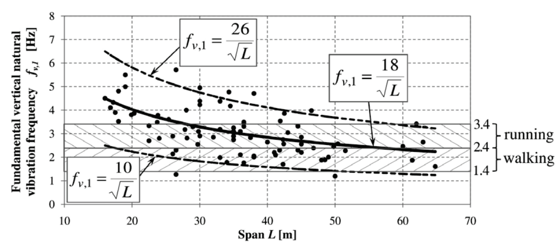

Figure 1: *Fundamental natural vibration frequency $f_{v,1}$ of steel and composite steel and concrete footbridges (own research results).*

As indicated by numerous dynamic field tests of timber footbridges, the dynamic susceptibility of these structures is much lower than steel and composite steel and concrete structures.

The lower dynamic susceptibility of timber footbridges to dynamic impacts of users results from their relatively high stiffness and, thanks to this, high value of their natural vibration frequencies as well as their ability to quickly dissipate energy (high value of the vibration damping coefficient).

It is worth remembering that in the case of resonant vibrations, the vibration amplitude is inversely proportional to the vibration damping coefficient. In other words, a large value of the vibration damping coefficient

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leads to a decrease in the vibration amplitudes of the structure.

The paper presents the results of numerous dynamic field tests of timber footbridges of various structural solutions. Basic dynamic characteristics of timber footbridges are presented, i.e., basic vibration frequency, damping, and the maximum dynamic response of the structure (maximum vibration acceleration) for various operating conditions.

2 DYNAMIC FIELD TESTS

Dynamic field tests of 25 footbridges were carried out for normal and exceptional operating conditions of the structure. Under normal operating conditions, the vibrations of the tested structure were induced by people walking or running with the step frequency f_s defined as normal for a given type of activity. Normal step frequency for walking was assumed to be f_s = 1.75 Hz [5]. Normal step frequency for running was assumed to be f_s = 2.65 Hz [5].

In exceptional operating conditions, the vibrations of the tested structure were induced by squatting. The frequency of human activity in exceptional operating conditions was assumed to be equal to the natural frequency of the tested structure in order to induce resonant vibrations of the structure.

In the first stage of the research, in order to determine the fundamental vertical natural vibration frequency of the structure, a person positioned in the middle of the footbridge span and in the middle of the footbridge deck made a series of unrestrained (unsynchronized) jumps.

In order to identify the frequency of torsional vibrations, the person jumping was positioned near the edge of the footbridge deck. Identification of the frequency of transverse vibrations was carried out by affecting the structure of the transverse force generated by the lateral displacement of the body by the person inducing the vibrations with the simultaneous impact of the foot on the footbridge deck.

The pre-identified natural frequencies of the structure were then confirmed by subsequent tests involving the excitation of resonant vibrations of the structure through dynamic actions in the form of jumps, running and transverse body swaying. The correct value of the frequency of activity was indicated by an electronic metronome.

The vibrations of the structure (vibration acceleration) were collected using portable data loggers (portable accelerometers) with a sampling frequency of 200 ÷ 1000 Hz.

Based on the collected vibrations of the footbridge deck induced by a person running along the entire length of the footbridge with resonant frequency of steps, the identification of the number of vibration extremes of the footbridge was carried out, and thus the mode shape of the footbridge was identified.

3 CHARACTERISTIC OF TESTED FOOTBRIDGES

Dynamic field tests were carried out on slab, beam, truss, arch, cable-stayed and suspension timber footbridges with a span length of 12.0 ÷ 50.0 m. General views and parameters of the tested footbridges are shown in Figure 2.

a) Växjö, Sweden
Stress laminated timber
L = 12.0 m
f_v= 7.1 Hz, δ = 37.0%

b) Växjö, Sweden
Stress laminated timber
L = 16.0 m
f_v= 3.5 Hz, δ = 30.0%

c) Växjö, Sweden
SLT deck supported by 5 glulam girders
L = 25.0 m
f_v= 4.3 Hz, δ =10.2%

d) Muszyna, Poland
2 glulam girders
L = 21.6 m
f_v= 5.4 Hz, δ = 13.0%

e) Muszyna, Poland
2 glulam girders
L = 21.6 m
f_v= 5.6 Hz, δ = 11.0%

f) Muszyna, Poland
2 glulam girders
L = 32.7 m
f_h= 1.4 Hz, δ = 9.5%
f_v= 2.9 Hz, δ = 7.7%

g) Karolinka, Czechia
2 glulam girders
L = 37.5 m
f_v= 3.2 Hz, δ = 9.5%

h) N. Hrozenkov, Czechia
2 glulam girders
L = 24.0 m
f_v= 4.7 Hz, δ = 7.0%

i) Pardubice, Czechia
2 double glulam girders
L = 43.5 m
f_h= 1.9 Hz, δ = 8.8%
f_v= 4.7 Hz, δ =10.4%

j) Husinec, Czechia
2 truss girders
L = 19.0 m
f_h= 1.8 Hz, δ =15.5%
f_v= 5.1 Hz, δ = 16.8%

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k) 

Hovmantorp, Sweden
2 truss girders
L = 19.0 m
f_v= 4.4 Hz, δ =20.6%

l) 

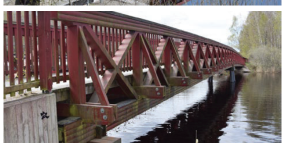
Växjö, Sweden
2 truss girders
L = 19.3 m
f_v= 4.2 Hz, δ = 13.8%

m) 

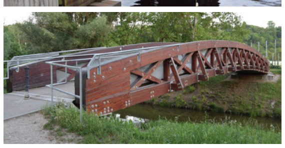
Växjö, Sweden
2 truss girders
L = 22.2 m
f_v= 4.2 Hz, δ =13.3%

n) 

Växjö, Sweden
2 truss girders, 3 simple supported spans
L = 3 x 26.4 m
f_v= 3.5 Hz, δ = 14.0%

o) 

Växjö, Sweden
2 truss girders, 2 simple supported spans
L = 2 x 28.5 m
f_v= 4.5 Hz, δ = 8.4%

p) 

Brno, Czechia
2 truss girders
L = 28.5 m
f_v= 4.1 Hz, δ = 7.1%

q) 

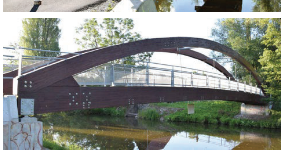
C. Budějovice. Czechia
2 truss girders
L = 33.0 m
f_v= 6.4 Hz, δ = 24.5%

r) 

Muszyna, Poland
2 tied-arch girders
L = 27.5 m
f_v= 3.5 Hz, δ = 7.8%

s) 

Cheb, Czechia
2 arch girders
L = 28.0 m
f_v= 3.8 Hz, δ =8.2%

t) 

Brno, Czechia
2 tied-arch girders
L = 28.0 m
f_v= 5.3 Hz, δ = 8.6%

u) 

Stožec, Czechia
2 tied-arch girders
L = 36.0 m
f_v= 3.9 Hz, δ = 10.0%

v) 

Val. Meziříč, Czechia
2 tied-arch girders
L = 37.5 m
f_v= 3.8 Hz, δ = 7.0%

w) 

Příbor, Czechia
Cable-stayed footbridge
L = 4.0 + 39.0 m
f_v= 3.0 Hz, δ = 3.3%

x) 

StaréHutě, Czechia
Cable-stayed footbridge
L = 38.0 m
f_v= 2.5 Hz, δ = 6.8%

y) 

Semily, Czechia
Suspension footbridge
L = 50.0 m
f_h= 1.0 Hz, δ = 19.6%
f_v= 3.1 Hz, δ = 2.6%

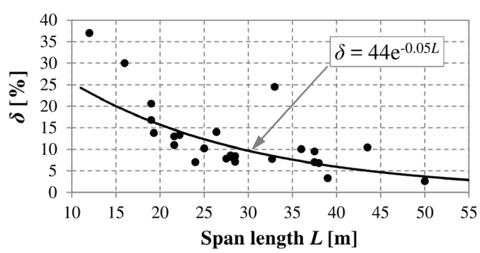
Figure 2: *General views and parameters of 25 tested footbridges (L – span length, f_v – vertical vibration frequency, f_h – horizontal vibration frequency, δ – mean value of the logarithmic decrement of damping)*

4 TESTS RESULTS

For all tested footbridges, the basic natural frequencies, the maximum vibration accelerations for normal and exceptional conditions of use and the values of the logarithmic decrement of vibration damping were determined.

In Figure 2, the basic natural frequencies and the values of the logarithmic decrement of vibration damping are presented. In most of the tested footbridges, the basic form of vibration was vertical vibration. In the case of four footbridges, the basic form of vibrations was horizontal vibrations transverse to the longitudinal axis of the structure (Figure 2 f, i, j, y).

The value of the logarithmic decrement δ was determined using the free vibration decay method.

a) 

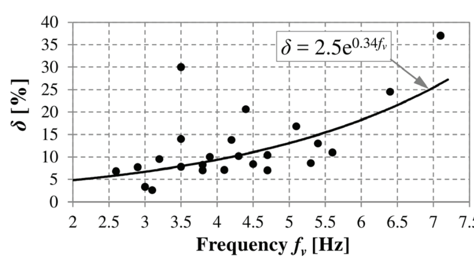
b) 

Figure 3: *Variation of the logarithmic decrement of damping δ for vertical vibrations (mean values) with the corresponding regression lines and equations: a) δ as a function of span length L, b) δ as a function of vibration frequency f_v.*

The δ values were determined on the basis of vibration acceleration signals, recorded during excitation of

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vibrations by one person running (the person inducing the vibration was leaving the structure, the vibrating structure was loaded only by its self-weight). Parts of the recorded vibration accelerations representing free vibrations of the structure were used to determine δ. Filtered vibration acceleration signals were used in the analyses. The Butterworth low-pass filter of order 4 and a cut-off frequency of 10 Hz was used. The final value of δ was determined as the average of 5 ÷ 8 measurements at each bridge. Figure 3 shows the variability of the logarithmic decrement of damping for vertical vibrations as a function of the span length and vibration frequency for the 25 bridges.

The dynamic responses of all footbridges were tested in normal and exceptional operating conditions.

Figure 4 shows examples of vibrations accelerations of footbridges decks recorded under normal operating conditions, i.e., vibrations induced by people walking with a step frequency $f_s = 1.75$ Hz and people running with a step frequency of $f_s = 2.65$ Hz.

Figure 5 shows examples of vibration accelerations of footbridge decks recorded under exceptional operating conditions, i.e., vibrations induced by people doing squats in place with a frequency corresponding to the natural vibration frequency of the structure (resonance).

Figures 4 and 5 show the vibrations of the footbridges presented in Figure 2c and n.

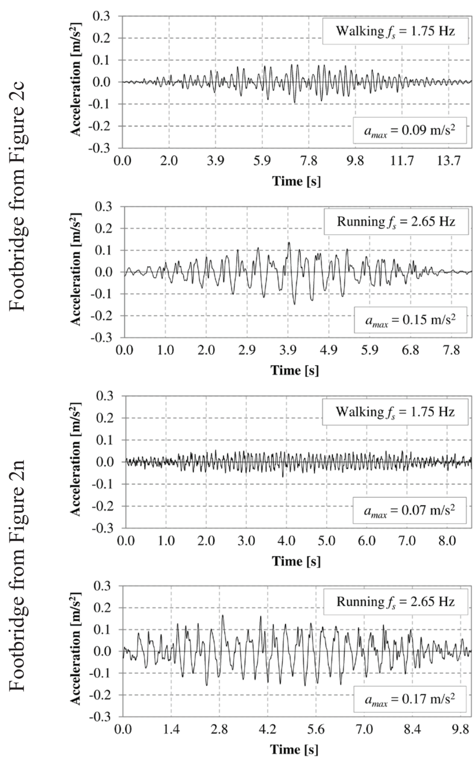

Figure 4: *Examples of vibration acceleration induced by a person walking and running with step frequencies $f_s = 1.75$ Hz and $f_s = 2.65$ Hz.*

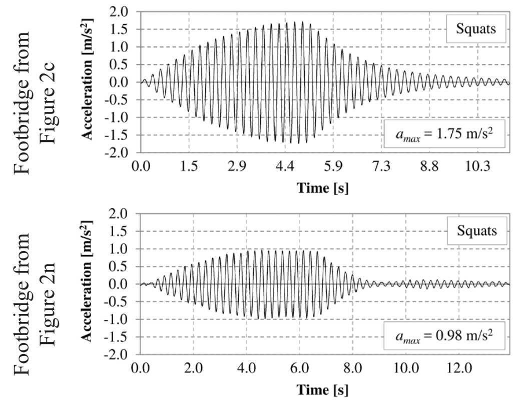

Figure 5: *Examples of vibration accelerations induced by a person doing squats with a frequency corresponding to the natural vibration frequency of the structure.*

Table 1 presents the values of the maximum vibration acceleration obtained on each of the examined footbridges. The given values were read from the filtered vibration acceleration signal.

Figure 6 presents the results from Table 1 in relation to various comfort levels for vertical vibrations [4, 6, 7]:

- $a_{max} \leq 0.5$ m/s^2: maximum comfort –vibrations are imperceptible to users, dotted line in Figure 6;
- $0.5 < a_{max} \leq 1.0$ m/s^2: average (medium) comfort – vibrations are slightly felt by users, dashed line in Figure 6;
- $a_{max} > 1.0$ m/s^2: minimum comfort – vibrations are clearly felt by users, vibrations disturbing walking, acceptable only in case of the occasional occurrence, area above dashed line in Figure 6;
- $a_{max} < 5.0$ m/s^2: structure safety level – maximum acceptable vibration level defined for exceptional events such as acts of vandalism (jumps, squats), vibrations are clearly felt by users, comfort of using the structure is strongly disturbed, free walking is impossible, standing or running is difficult and strongly disturbed, dash-dotted line in Figure 6b.

Table 1: *Dynamic response of the footbridge under normal and exceptional operating condition*

Footbridge from Figure 2	Vibration acceleration [m/s^2]		
	Walking $f_s = 1.75$ Hz	Running $f_s = 2.65$ Hz	Squats
a)	0.03	0.07	0.63
b)	0.05	0.11	0.53
c)	0.09	0.15	1.75
d)	0.11	0.27	1.96
e)	0.16	0.39	2.15
f)	0.12	0.53	2.86
g)	0.06	0.14	1.57
h)	0.08	0.41	2.43
i)	0.14	0.34	2.21
j)	0.12	0.28	1.28
k)	0.04	0.15	0.84
l)	0.06	0.21	1.15
m)	0.08	0.23	1.68

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n)	0.07	0.19	0.98
o)	0.12	0.32	1.36
p)	0.07	0.47	1.18
q)	0.04	0.12	0.56
r)	0.11	0.41	2.77
s)	0.18	0.55	2.32
t)	0.08	0.43	1.56
u)	0.06	0.23	1.31
v)	0.07	0.53	3.48
w)	0.11	0.48	2.35
x)	0.14	0.87	1.67
y)	0.16	0.51	1.31

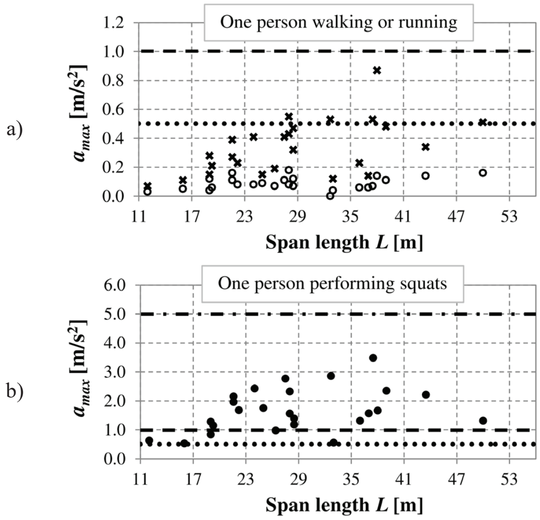

Figure 6: *Vertical vibration accelerations of the tested footbridges in relation to comfort levels for a) vibrations induced during walking (circles) and running (x mark), and b) vibrations induced during squats (comfort levels explained in the text).*

Figure 7 presents vertical vibration accelerations of the tested footbridges for normal operating conditions in relation to the vibration frequency and the level of maximum comfort of using the structures.

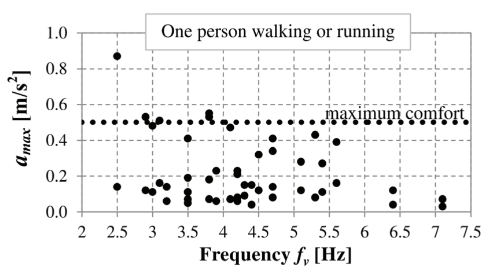

Figure 7: *Vertical vibration accelerations of the tested footbridges for normal operating conditions in relation to the vibration frequency and the level of maximum comfort of using the structures (dotted line).*

5 SUMMARY AND CONCLUSIONS

The tested timber footbridges are characterised by relatively high damping. The logarithmic decrement of damping δ for 70% of the tested footbridges is in the range of 5 ÷ 15%. The obtained results are in accordance with the recommendations of [8] according to which the δ value for wooden bridges is in the range of 6 ÷ 12%.

Regression lines presenting the variability of δ for vertical vibrations, in relation to the footbridge span length as well as vibration frequency (Figure 3), seem to be appropriate to determine the value of logarithmic decrement of damping of timber footbridges. These results can be used in dynamic analyses of timber footbridges.

Two of the tested SLT footbridges showed exceptionally high damping of 30 ÷ 40%. This result is interesting and worth confirming by further research of SLT structures. In the light of the results of field tests, the SLT technology seems to be beneficial from the point of view of the dynamic resistance of footbridges to dynamic impacts of users. The high value of vibration damping ($\delta \approx 30 \div 40\%$) has a positive effect on reducing the vibration amplitudes of the structure. The achieved effect probably results from the presence of many planes of cooperation of elements in the SLT structure that allow for effective energy dissipation. The presented result was obtained for a structure with a short span length. It will be interesting to perform vibration damping analyses in SLT structures with larger spans. However, high self-weight of the SLT structure may lead to a significant reduction in their natural vibration frequency and an increase in their dynamic susceptibility. This subject requires further research and analyses.

The natural frequencies of the presented glulam beam, truss and arch footbridges reached values of $f > 3.0$ Hz and relatively high values of the logarithmic decrement of vibration damping δ = 7% ÷ 20% (about 4 ÷ 10 times higher than δ for welded steel structures $\delta \approx 2.0\%$). This effectively reduces the risk of excitation of their vibrations by users.

In the case of the presented cable-stayed and suspension footbridges, the values of frequency and vibration damping are lower than in other tested objects. Comparison of the results achieved for cable-stayed and suspension footbridges with the results achieved for other tested structures indicates the presence of an increased risk of their dynamic excitation by users. However, the data set is too small to draw clear conclusions about structures of this type. Vibration accelerations induced on the cable-stayed and suspension structures by walking people were within the range of maximum comfort. Vibration accelerations induced on these structures by runners were in the range of average comfort. Also, intentional excitations of vibrations by squats did not cause significant vibrations of the structure. The vibrations induced during squats remained in the range of minimal comfort. In the case of a rare occurrence, they can be considered acceptable. The analysed cable-stayed and suspension structures are either characterised by relatively high frequency and low damping or low frequency and high damping. The high frequency of natural vibrations or the relatively high vibration damping value ensured the appropriate dynamic resistance of these structures.

The obtained results of the dynamic tests indicate relatively high dynamic resistance of timber footbridges to the dynamic loads generated by users under normal

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conditions of use. The induced acceleration of vibrations only in rare cases lightly exceed the level of maximum comfort specified for the moving people for vertical vibrations. If the maximum comfort level is exceeded, the structure's vibrations remain in the medium comfort area. This means that under normal conditions of use of the analysed structures, their vibrations are not felt by users.

The amplitudes of vibrations intentionally induced by people doing squats (resonant action) exceed the level of minimum comfort. However, these vibrations do not reach the limit value due to the safety of use of the structure. Compared to the results obtained for steel footbridges (vibration acceleration induced by one squatting person in the range of 3.0 ÷ 8.0 m/s^2), the obtained results prove the relatively high resistance of timber footbridges to intentional excitation of vibrations. The explanation of this situation can be found in two factors: in the high value of the ratio of self-weight of the structure to the value of moving loads (G/Q = self-weigh/pedestrians' weight) and in the relatively high value of structural damping.

In addition, on the basis of the obtained results, in the case of timber footbridges, it seems appropriate to verify the requirements of international standards [1] defining the range of natural frequencies sensitive to the dynamic impact of users. In the case of timber footbridges characterized with relatively high self-weight, stiffness and damping, it seems reasonable that the dynamic analyses should be required for structures with a fundamental vertical vibration frequency $f_v \leq 3.0$ Hz instead of the currently defined $f_v \leq 5.0$ Hz.

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